Singapore 2nd National Climate Change Study – Phase 1

Executive Summary

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Executive Summary

As the evidence of impacts arising from climate change continues to mount, there is an increasing need for nations to have access to information that aids planning and adaptation action to reduce risks of potential future consequences. This is particularly the case for island nations such as Singapore where the potential challenges arise from both land and ocean climatic changes. The 2nd National Climate Change Study for Singapore aims to provide information on anticipated climate change that can inform the discussion and decision-making around the actions that are required to safeguard the population, environment and infrastructure.

This study comprises the first of two phases, providing projections of changes in the main climate variables of interest to Singapore. The second phase will assess the vulnerability of different sectors in Singapore to future climate change, through analysis of impacts resulting from the climate changes projected in this study. The results will be used to underpin the next stage of national adaptation planning.

The centrepiece of the study is the provision of an ensemble of regionally downscaled climate and sea level projections over the region centred on Singapore, out to 2100, and driven by the latest available climate models. This ensemble is complemented by a smaller set of very high resolution modelling runs to provide confidence in the information on daily rainfall extremes from the main 12 km downscaled projections, together with a broader assessment of uncertainties in future climate change obtained by combining results from different climate model ensembles. A view on plausible longer term changes for sea level, temperature and precipitation out to 2300 is also provided.

This work was commissioned by the National Environment Agency (NEA) in Singapore, and was undertaken by the Met Office Hadley Centre in the UK jointly with scientists from the Centre for Climate Research Singapore (CCRS) and included important contributions from the National Oceanography Centre, Liverpool (NOC), and the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) for the sea level projections.

The following paragraphs provide a summary of the main conclusions from each section of the study. Full details can be found in the Science Report.

Stakeholder engagement

A key consideration in delivery of such a study is to understand the intended uses of the climate projections at an early stage to enable an experimental design to be developed that addresses the needs of key stakeholders. Stakeholder engagement was sought during the initial stage of the study, with a particular emphasis on the intended use of the resulting information in subsequent impacts studies. Hence the project was developed with an awareness that data produced would feed into vulnerability and impact studies, which in turn would inform resilience action plans and construction of a climate change risk register.

Stakeholder engagement was primarily sought across six thematic clusters:

- Coastal Protection
- Water Resources and Drainage
- Biodiversity and Greenery
- Public Health
- Building, Structure and Town Infrastructure
- Network Infrastructure

Representatives were drawn from the relevant Singapore government agencies providing a wide cross-section of users. The broad stakeholder base, combined with the consultation early in the project, ensured that, as far as is possible, subsequent work has been shaped to deliver outcomes that are of value to stakeholders and decision-making activities.

Overall approach

The starting point for generating projections of climate change at regional and local scale is the global-scale projections produced by General Circulation Models (GCMs). The most recent generation of GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012) have been used. These are the same models that provided the climate model projections that were assessed as part of evidence for the findings of the Intergovernmental Panel on Climate Change's Fifth Assessment WG1 Report (hereafter "AR5", IPCC, 2013). The CMIP5 database comprises historical and future climate projections from the most up-to-date global modelling systems in use by the leading climate modelling groups around the world.

Dynamically downscaling the global models will add regional detail. This has an advantage over other techniques in being able to provide spatially and temporally coherent forcing data for downstream models, such as wave and surge model simulations and in impacts models of interest to stakeholders. In this study dynamically downscaled climate projections provide comprehensive information on plausible future climates for Singapore and form the majority of the evidence base to inform planning and decision-making. The centrepiece is the provision of an ensemble of regionally downscaled climate and sea level projections over the region centred on Singapore, out to 2100, and driven by the latest available climate models. In addition this study involves:

- Use of very high resolution modelling to provide confidence in the information on daily rainfall extremes from the main 12 km downscaled projections.
- A broader assessment of uncertainties in future climate change obtained by combining results from different climate model ensembles to provide further context for the downscaled projections.
- A view on plausible longer term changes for sea level, temperature and precipitation out to 2300.

Model sub-selection

The generation of regional climate model simulations is computationally expensive. The CMIP5 ensemble comprises around 40 climate models, providing a range of realisations of the future climate. It is neither feasible in terms of cost, nor desirable to downscale the full ensemble of CMIP5 global simulations because some of these simulations are unrealistic over the region of interest, and others exhibit similar climate responses. By carefully selecting a sub-set of 10 of the available models, we generated a set of plausible future climate scenarios which represent the range of uncertainty in the CMIP5 GCM ensemble, and are therefore consistent with the most up-to-date projections assessed in the IPCC AR5. This sub-selection uses an assessment of both the degree of realism in the representation of the baseline climate and the changes in climate projected by each model.

All models were assessed for their ability to represent key aspects of climate in the region including: the southwest and northeast monsoon circulations, the migration of the Inter-Tropical Convergence Zone (ITCZ), regional rainfall patterns, sea-surface and near-surface air temperatures and key modes of variability – the El Niño Southern Oscillation (ENSO) and The Madden Julian Oscillation (MJO). The final sub-set of 10 models was selected to most efficiently span the range of projected future changes in regional average temperature and precipitation, whilst also spanning the range of changes in monsoon circulation, ENSO variability, ITCZ position and intensity and tropical cyclone behaviour.

Dynamical downscaling experimental design

The regional climate model used for dynamical downscaling is HadGEM3-RA configured to run over a 12 km horizontal resolution grid centred on Singapore, and covers much of Southeast Asia. This model has been applied over many other land regions of the globe and draws upon the extensive model development expertise that has contributed to the development of the HadGEM family of general circulation models.

The ability to drive the model using lateral boundary data derived from a subset of the CMIP5 GCMs is a new development that posed both scientific and technical challenges. Some aspects of the model formulation, most notably the vertical level configuration, have been constrained to match those of the driving GCMs. The evaluation of the simulations has paid particular attention to the performance of HadGEM3-RA when downscaling global models with different physical and numerical formulations.

For each of the selected CMIP5 GCMs, three experiments have been run following the experimental design used in CMIP5, one historical simulation and two future simulations based on different Representative Concentration Pathways (RCPs), RCP8.5 and RCP4.5.

In addition, a simulation forced by boundary data derived from the ERA interim reanalysis and observed SSTs was completed for the period 1982-2010 to allow evaluation of the regional model when driven by quasi-observed boundary conditions.

Model evaluation

Simulations of the historical period have been evaluated to (a) check their scientific integrity, and (b) assess how well they relate to observed climate in order to provide useful contextual information for users of both the historical simulations and the future projections.

An important measure of the overall scientific integrity is the level of consistency between large-scale geographical and temporal patterns in the downscaled GCM and the driving GCM. For nine of the models, the consistency in large-scale variables was found to be satisfactory, providing evidence that the experimental design is suitable for use in producing climate scenarios. For the tenth model, GFDL-ESM2G, the consistency was less satisfactory and the decision was taken to exclude this simulation from further use in the study.

Comparison of the downscaled simulations with available observations show a variety of moderate systematic biases which vary across different models, seasons, regions, and variables. While most variables are broadly realistic, a significant shortcoming that affects all simulations is the representation of heavy rainfall events over land. Here the 95th percentile of daily rainfall is reduced by 50% or more compared with observations in many regions. There is a clear land-sea contrast in the magnitudes of the heaviest rainfall events, with magnitudes over the oceans being closer to those observed. This has been linked to the representation of convection over land, which is a common problem in climate models, including in the GCMs used in this study.

Some key processes that are known to have important effects on Singapore's climate were assessed in the downscaled simulations. The simulations were found to capture the variability and duration of cold surges well, but underestimate their frequency. The models represented the broadscale patterns of precipitation associated with cold surges realistically, but lacked the enhanced precipitation that is observed over the Malaysian Peninsula during these events. The El Niño Southern Oscillation (ENSO) is another key mode of variability that directly impacts the climate of Singapore. Future changes in ENSO could substantially change droughts affecting the region; however, there is not enough confidence in the projected changes in ENSO in the CMIP5 ensemble (as stated in the 5th Assessment Report) to draw conclusions.

Comparison of the local-scale simulated climate of Singapore and its immediate surroundings with both station and satellite observations indicated the following characteristics:

- Enhanced land-sea contrast in mean precipitation, with higher values over the ocean, and lower than observed values over the land.
- Reduced number of days with little or no rainfall.
- Significantly reduced heavy rainfall events over land grid-points, but realistic values over the ocean grid points.
- A narrower diurnal temperature range simulated by models than observed, with reduced maximum daily temperatures, and increased daily minimum temperatures.

Projections of changes in heavy rainfall are of particular importance to Singapore. The shortcoming of their simulations over land means that direct model projections of changes in extreme rainfall over Singapore land grid points cannot be used. By contrast, model simulations of extreme rainfall over the nearby oceans is broadly realistic. In reality the maritime nature of Singapore's climate means that the cumulative density function of rainfall intensities over Singapore land and over the nearby ocean are very similar. This fact is used to deduce future changes over land from changes over the nearby oceans.

Climate Change Projections

The assessment of the performance of the model simulations during the historical period provides context for the interpretation of the future projections. The wider Southeast Asian region analysis focuses on assessing changes at monthly and seasonal scales of average temperature, precipitation and lower tropospheric circulation, including important summary measures of changes in maximum and minimum daily temperatures, heavy precipitation, dry seasons and high 10m wind-speeds. The regional results are used to put the projections for the Singapore region in the wider context of changes taking place across Southeast Asia. The analysis for the Singapore region focuses on changes in daily precipitation, temperature, relative humidity and wind. The RCM data covering grid points over Singapore have been bias-corrected based on local station observations.

As expected from the IPCC AR5 results, the most robust aspects of the climate change projections for the Singapore region are the increases in near surface temperature. Relative to a reference period of 1980-2009, daily mean temperatures are projected to increase by around 2°C (RCP4.5) to 4°C (RCP8.5) for the end-century period (2070-2099). This will lead to temperatures significantly higher than those currently experienced. A seasonal analysis of warm days and nights for February to May (having the highest number of warm days in the current climate) and June to September (having the highest number of warm nights in the current climate) shows that the models project significant increases in both throughout the 21st century. In the case where the world follows an RCP8.5 greenhouse gas trajectory, most models project that by the end-century almost every day in these seasons on average would be classified as a warm day (≥34.1°C) and having a warm night (≥26.2°C).

Also consistent with the IPCC AR5 results, The projections for precipitation changes are far less robust than those for temperature. Analysis of annual mean rainfall changes over Singapore shows considerable variation amongst models, ranging from positive to negative, independent of the RCP that is used. In all cases, the projected long-term trend is smaller than the natural variability as simulated in the models, suggesting that Singapore's annual average rainfall will continue to be dominated by natural variability during the 21st century.

On a seasonal basis, the contrast between the wetter and drier months is projected to become more pronounced, especially for the RCP8.5 trajectory and by the end of the century. The models generally project an upward trend in seasonal mean rainfall during the wet season of November to January, as well as greater dryness during months that are already relatively drier in the current climate (February and June to September). Another important result from these projections is that most models show an increasing trend in the intensity and frequency of heavy rainfall events as the world warms. This is consistent with our current state of physical understanding that the frequency and intensity of heavy rain events increase in a warmer atmosphere with a higher water vapour content.

In terms of future changes in the wind, the climate of Singapore will continue to be dominated by the northeast and southwest monsoons. By the end of the century, there are no substantial changes in wind direction but there is some indication of increasing wind speeds during the northeast monsoon season under RCP8.5. A single very high resolution model simulation suggests that by the end of the century, under RCP8.5, there could be a small increase in wind gust strength (of the order of 5-10%).

Convective-Scale Modelling

In order to explore the sensitivity of the results to the regional model resolution, a higher resolution convection-permitting model in the dynamical downscaling approach has been used. This is particularly important because the region is dominated by localised convection which is not well represented in the current generation of models, and also to better represent the complex coastlines and topography which may be under-represented in the 12 km model. These experimental simulations provide some additional insight to aid the interpretation of the 12 km regional climate model results.

To assess the potential benefits of using a convective-scale, dynamically-downscaled model to simulate the local climate of Singapore, a 1.5 km resolution regional climate model (RCM) has been nested within one of the 12 km RCMs used in projections, with an intermediate nest of 4.5 km resolution. The ability of the 1.5 km model to simulate the present day climate is assessed through an analysis of an ERA-interim driven simulation, whilst the projected climate change from this RCM is assessed in present day and RCP8.5 simulations driven by HadGEM2-ES. The three simulations are all ten years in length (their duration is limited by the computational expense of the convective-scale RCM) and the results presented focus on the realism of the simulated rainfall, in terms of the mean climate and the ability of the RCMs to simulate extremes. The simulation of extreme rainfall events is greatly improved in the 1.5 km RCM consistent with previous studies over the UK (Kendon et al., 2012).

These simulations are only 10 years in length, and there is considerable decade-to-decade variation in the results. It is therefore not possible to make direct quantitative comparisons of these results with those from the 12km resolution bias corrected projections. Despite this, the increase in upper percentile heavy rainfall events is found to be a robust feature in the projections. End-of-century projections for hourly rainfall intensity and duration show a significant increase in the occurrence of heavy rainfall events (intensities exceeding 20 mm hr^{-1}) over both land and sea in the 1.5 km RCM. In contrast, for the 12 km RCM the increased occurrence of rainfall is limited to rainfall intensities less than 10 mm hr^{-1}.

In the 1.5 km RCM, the rainfall distributions are similar over Singapore land points and the nearby ocean point that was used for bias-correction of the 12 km precipitation outputs. This supports the use of the precipitation at the ocean grid point as a proxy for the precipitation in the bias-correction of the precipitation outputs from the set of nine 12 km RCM climate projections over Singapore.

Statistical Downscaling

An alternative approach to deliver projection information at specific locations is to use statistical downscaling of large-scale model results, which also can provide an opportunity to obtain downscaled projections from a wider range of CMIP5 models than can be covered using the dynamical downscaling approach.

The results show that good quality statistical models based on linear regression models can be calibrated from the observed climate for mean daily temperature, minimum and maximum daily temperature and wind speed. Reasonable quality projections can be established for these variables when using bias corrected GCM data. The stability of these statistical models has been tested by using RCM grid-box variables from a GCM-driven projection as a proxy of observed variables. This test has shown that downscaled projections constructed from the simulated present climate reproduced quite well the simulated RCM variables for the future period. With some caveats, the regression model is assessed as suitable for use in downscaling other GCMs for these variables. With an assumption that the statistical relationships from the calibration period continue to hold for the future climate, the methodology could provide downscaled projections for these variables. For precipitation, which comes largely from convective local systems, the methodology was not able to produce acceptable calibration relationships between large-scale drivers and local rainfall for Singapore hence is deemed unsuitable for rainfall downscaling. For this reason, a set of statistically downscaled projections for this variable have not been produced in this study. For all the other variables, the statistical downscaling methodology is not efficiently reproducing the tails of their distributions and it could be of limited use to assess the effects of climate change over Singapore and for impact studies which are strongly dependent on daily extremes.

Probabilistic Projections

The dynamical downscaling experimental design has been selected to sample the range of uncertainty in future projections within the CMIP5 ensemble. However, simulations of climate change are subject to several sources of uncertainty from a) different emissions scenarios, b) uncertainty in the way climate models respond to a given set of emissions, and c) climate variability. The regional climate simulations provide useful information to stakeholders but partially sample these three sources of uncertainty. Thus, it is important to understand the extent to which they under-represent a wider range of uncertainties associated with climate change projections. This wider uncertainty can be considered to represent a broader range of plausible outcomes consistent with current understanding of earth system processes likely to affect future climate, and that are sufficiently well understood to be included in contemporary climate or earth system models.

To represent this for Singapore, probability density functions (PDFs) have been generated using the three-stage method that was used to make probabilistic climate projections for the UK in 2009 (UKCP09). The method is based on a wider ensemble including ensembles of the Met Office Hadley Centre model HadCM3, CMIP5 and CMIP3 simulations from other climate modelling centres generated for the fourth IPCC assessment. This method has been validated for temperature changes which are driven at least in part by large scale climate drivers. However, due to the difference in response between HadCM3 and most CMIP5 models, it was not possible to produce robust PDFs for precipitation changes.

The temperature PDFs represent uncertainties in response to future greenhouse gas emissions, and therefore account for carbon cycle as well as physical climate feedback processes. For annual mean precipitation changes, the 9 CMIP5 models used in the dynamical downscaling are representative of the range of changes across all CMIP5 and HadCM3 variants. However, for JJA, some HadCM3 model variants are drier than the driest response in the 9 CMIP5 models. For NDJ, there are some CMIP5 models with a wetter response than those seen in the 9 models used in the dynamical downscaling.

Mean and Extreme Sea Level Projections

The dynamically downscaled projections and accompanying investigations provide a comprehensive view of the likely changes in atmospheric climate parameters out to the end of the century. However, as an island nation there is a particular requirement within Singapore to understand the concurrent marine changes, in particular changes in sea level and associated risk of extreme coastal events. Changes in frequency and severity of extreme coastal events are determined from combining changes in large-scale time-mean sea level and characteristics of the wave and storm surge conditions that affect the coastline. These two factors have been considered in turn to project changes in future extreme water levels near the coast of Singapore for use in local impacts studies.

Projected changes in large-scale time-mean sea level for the Singapore region over the 21^{st} Century under the RCP4.5 and RCP8.5 climate change scenarios have been assessed based on climate model simulations from CMIP5 and "fingerprint" patterns from numerical models of the solid Earth response to both past and future terrestrial ice mass loss and changes in terrestrial water storage.

The most relevant definition of sea level for assessing impacts is that which is relative to adjacent land areas. As such, local vertical land movements of any origin should be taken into consideration though the only vertical land movement process assessed here is the viscous Earth response to the last de-glaciation (glacial isostatic adjustment, GIA). We therefore recommend that any impacts assessments seek further information on current vertical land movement observations and the underlying processes. Of particular note is the proximity of Singapore to the tectonically active Sumatra fault.

Projections of time-average sea level for Singapore far exceed water levels associated with simple extrapolation of long-term trends from local tide gauges. The central estimates for projected time-mean sea level rise for Singapore are very similar to the global rates presented in the AR5 For mean sea level rise for 2100, a median estimate of 0.53 m is projected under RCP4.5 and 0.73 m under RCP8.5. Up to 2050, the ranges of regional projections of mean sea level rise in the RCP4.5 and RCP8.5 scenarios are similar, with a median value of approximately 0.25 m. Even at 2100 there is substantial overlap between the ranges of projected rise from the two RCPs. The projections presented here do not consider the unlikely event of a collapse of the marine-based sectors of the Antarctic ice sheet. This event could result in additional global sea level rise of several tenths of a metre during the 21^{st} century. (AR5, Church et al., 2013).

Four out of the nine 12 km downscaled RCM sets of simulations were used to drive coastal models of the Singapore region to assess potential changes in waves and surge activity under the most severe climate change scenario used by AR5, RCP8.5. The projected century-scale trends in the extreme surges without considering the changes in mean sea level are not statistically significant. Our upper and lower estimates are modified to allow for uncertainties due to the small ensemble size. The upper estimate of the change in skew surge by 2100 is an increase of a few cm (compared with the upper estimate of over 1m for the change in mean sea level). A method is presented for combining the changes in mean sea level and surge with current return period estimates, to obtain upper, central and lower estimates of site-specific extreme still water levels through the 21^{st} Century. Trends in the largest waves at the Singapore coast over the 21^{st} Century are negative for all four models considered here, but allowing for the small ensemble size results in the possibility of increasing trends. Overall our results indicate that changes in extreme water levels for the Singapore region over the 21st Century are likely to be dominated by the regional time-mean sea level rise.

Longer term projections

The majority of the analysis in this study has focused on the likely changes out to the end of this century, which is sufficient for the majority of planning activities. There is, however, benefit in understanding the longer term context for these changes, and in gaining insight into possible scenarios for change over longer time horizons, e.g. for adaptation planning for long-term infrastructures.

Exploratory projections of temperature, rainfall and sea level rise for the Singapore region over the next three centuries (out to 2300) have been produced using the MAGICC simple climate model together with information from CMIP5 models and other data sources. In addition, we draw upon literature evidence to present a plausible high-end scenario (H++) for sea level rise, which lies outside the range of the model results presented. These results should be interpreted as a limited set of plausible outcomes provided by current climate models in combination with two extended emissions scenarios, both assuming stabilisation of greenhouse gas concentrations.

Projections of temperature change circa 2300 under the RCP8.5 scenario, relative to a 1961-1990 baseline period, range from about 5°C to 12°C. No robust signals in mean rainfall were identified. These results are consistent with the IPCC AR5 findings for changes over the 21st Century.

The lower and upper bounding ranges for sea level rise for Singapore at 2300 are 0.36 - 2.10 m (for RCP4.5 and low sensitivity to forcing) and 0.94 - 5.48 m (for RCP8.5 and high sensitivity to forcing) respectively. A plausible upper limit of range of sea level rise at Singapore of 3-6 m for 2300 is recommended for use in adaptation planning.

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